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Bidirectional cosmic ray and ∼1 MeV ion flows, and their association with ejecta

I. G. Richardson[1], **V. M. Dvornikov**[2], **V. E. Sdobnov**[2], **and H. V. Cane**[1]

[1]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[2]Institute of Solar-Terrestrial Physics, Irkutsk, Russia

Abstract. We have previously demonstrated that bidirectional galactic cosmic ray flows observed by the world-wide neutron monitor network during a particular year (1982) were well-correlated with bidirectional flows of ~ 1 MeV ions observed by near-Earth spacecraft, and with the passage of interplanetary coronal mass ejections. We discuss recent episodes of bidirectional flows of cosmic rays and ~ 1 MeV ions, and examine the associated solar wind structures.

1 Introduction

Energetic particles provide useful probes of the solar wind structures through which they propagate. Occasionally, bidirectional particle flows aligned with the magnetic field direction are detected. Such flows may indicate that the magnetic field lines on which they are detected are connected to a particle source at each end. Another possibility is that the particles are trapped on expanding looped field lines. As the field lines expand, the field-aligned velocities of the particles become enhanced at the expense of the perpendicular component (Palmer et al., 1978). Such bidirectional flows have been frequently observed by spacecraft during enhancements of ~ 1 MeV ions accelerated by solar events or interplanetary shocks (e.g., Richardson and Reames, 1993 and references therein). In particular, it has been found that these flows tend to be observed inside interplanetary coronal mass ejections (ICME), often termed "ejecta", the manifestation in the solar wind of the material associated with coronal mass ejections observed by coronagraphs at the Sun. Fast ICMEs may generate shocks ahead of them, which may accelerate energetic particles. The bidirectional flows suggest the presence of looped magnetic field lines in ICMEs. This is consistent with the frequent detection of bidirectional solar wind electron heat fluxes (BDEs) within ICMEs (Gosling et al., 1987) suggesting that ICMEs may include looped field lines rooted at the Sun at each end. Energetic particle flows during the onset of solar particle events observed by spacecraft inside ICMEs are also consistent with the presence of looped field lines rooted at the Sun (Richardson and Cane, 1996).

In a recent study (Richardson et al., 2000), we compared observations of bidirectional ~ 1 MeV ions made by near-Earth spacecraft during one year (1982) with intervals of bidirectional flows observed at cosmic ray energies (~ 4 GV). The cosmic ray flows were inferred by combining data from a world-wide network of 42 neutron monitors (NM) using the method of spectrographic global survey (Dvornikov and Sdobnov, 1997, and references therein) in which the NM network is regarded as a single multi-channel instrument. In this paper, we consider some more recent observations of bidirectional particle flows detected by the IMP 8 spacecraft and NM network, and again demonstrate a close association with ICMEs.

2 Instrumentation and Analysis

The spacecraft observations are from the Goddard Medium Energy (GME) instrument on IMP 8, which detects 0.5 - 4 MeV/amu and 4 - 22 MeV/amu $Z = 1, 2$ ions, and 1.7 - 12 MeV/amu $Z \geq 2$ ions in 8 azimuthal sectors as the spacecraft spins. The sectored counting rates, transformed into the solar wind frame, are fitted to a Fourier series in azimuth. The first- and second-order terms, a_1 and a_2 (normalized to the isotropic term a_0) represent the unidirectional and bidirectional streaming components. Bidirectional flows are identified by the criteria of Richardson and Reames (1993): $a_2/a_1 > 0.8$, $a_2/a_3 > 2$, and $a_2 > 0.1$. Analysis of the NM data is discussed by Dvornikov and Sdobnov (1997). Two-hour averaged, pressure-corrected data from the NM network are normalized to a suitable background level. Instrumental and geomagnetic effects and the coupling between primary and secondary cosmic rays are taken into consideration, and inverse power-law rigidity spectra are assumed. The cosmic ray distribution is expressed as a spherical harmonic se-

Correspondence to: I. G. Richardson
(richardson@lheavx.gsfc.nasa.gov)

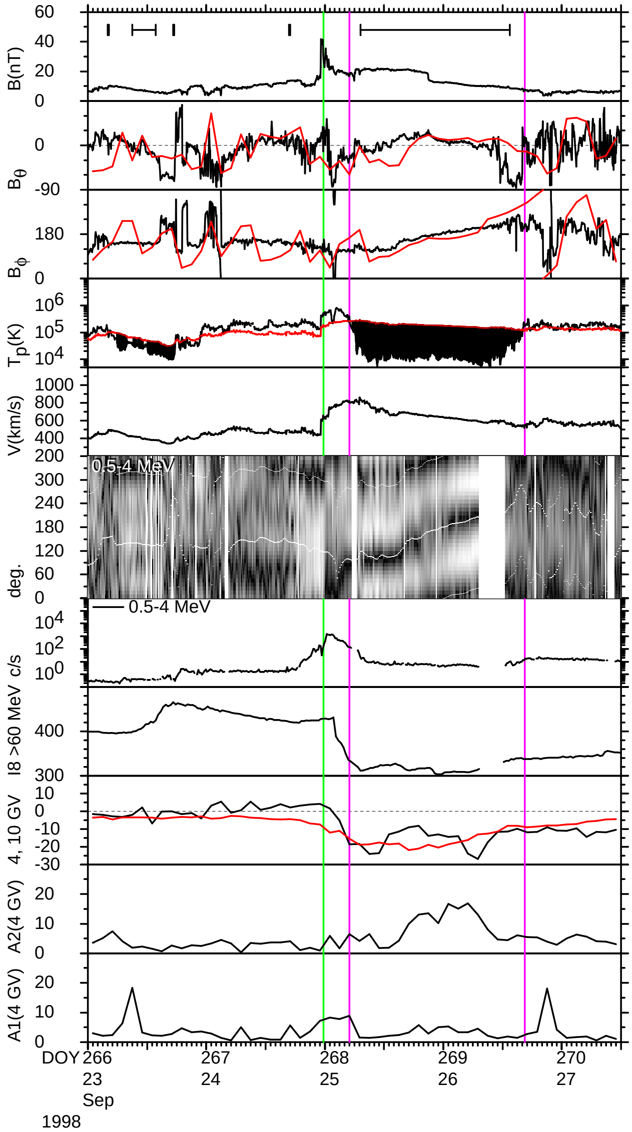

Fig. 1. Solar wind and energetic particle observations on September 23-27, 1998 showing bidirectional cosmic ray and 0.5-4 MeV ion flows inside an ICME. For description, see text.

ries. The amplitude $A_1(R)$ and direction (phase) of the first spherical harmonic correspond to the unidirectional streaming component for particles with rigidity R. (We use "a" for the ~1 MeV ions and "A" for the NM data.) The second harmonic $A_2(R)$ has three components: A_2^0 (which has no azimuthal dependence), A_2^1, and A_2^2. As in Richardson et al. (2000) we use two different set of criteria to identify bidirectional cosmic ray flows. In addition to requiring $A_2 > A_1$, we select periods with $A_2 \geq 8\%$, or with A_2^1 or $A_2^2 > 2\%$ (intending to exclude periods when the CR bidirectional flows were highly inclined to the ecliptic). In practice, each method identifies similar intervals.

3 Results

We have analysed data from the NM network for January 1997 - November 1998 and some additional intervals of interest. Because of the reduction in the number of operating stations since 1982, and non-availability of data from some other stations, the analysis is currently based on data from $\sim$ 25 NMs rather than the 42 used in Richardson et al. (2000). We identified a small number of intervals (7) that fulfilled the above criteria for bidirectional flows and extended over more than one 2-hr interval. The most extended interval (18-hr duration) occurred from September 25, 16 UT to September 26, 10 UT, 1998. The bottom two panels of Figure 1 show A_1 and A_2 at 4 GV for a period on September 23-27 including this interval. The panel immediately above shows the isotropic cosmic ray intensities at 4 and 10 GV obtained from the NM analysis which indicate that the bidirectional flows, indicated by enhanced values of A_2, occurred within a Forbush decrease. The remaining panels place this event in the context of simultaneous near-Earth solar wind and low-energy particle observations. The top panels show the magnetic field intensity, polar and azimuthal angles (GSE coordinates), solar wind proton temperature and speed, all from the ACE spacecraft. An interplanetary shock, indicated by the vertical green line, passed Earth at 2345 UT on September 24. The black shaded region in the T_p panel commencing $\sim$ 5 hours following the shock indicates that the plasma temperature is abnormally low, i.e., $T_p < 0.5T_{ex}$, where T_{ex} (indicated by the red line) is the temperature for "normally-expanding" solar wind, which is calculated from the well-established relationship between the solar wind speed and T_p in the solar wind (see references in Richardson and Cane, 1995). Such regions are often indicative of the presence of an ICME (Richardson and Cane, 1995). Thus, the low T_p region on September 25-26 indicates the ICME generating the shock on September 24. The next two panels show the angular distribution and direction-averaged counting rate of 0.5-4 MeV ions at IMP 8. In the angular distribution, particle count rates, smoothed using a third-order Fourier fit, are plotted vs. viewing direction (e.g., 270^o corresponds to flow from west of the Sun-Earth line) and normalized to the maximum intensity (darkest shading) in each 15-minute integration period. Directions parallel and anti-parallel to the magnetic field are indicated by the superimposed thin white lines. As has been previously noted (Richardson et al., 1999), an extremely clear period of bidirectional field-aligned $\sim$ 1 MeV ion flows occurred within this ICME, as indicated by double bands of darker shading along these directions. The horizontal bars in the top panel summarize the intervals of bidirectional streaming we have identified using all the IMP 8 data. The bidirectional cosmic ray flows at $\sim$ 4 GV are also approximately field-aligned, since the polar and azimuthal angles of the A_2 component (red lines) in panels 2 and 3 track the magnetic field direction reasonably well during the period of bidirectional flows. Finally in Figure 1, we show the counting rate of the IMP 8 GME anti-coincidence guard, which responds to $>$ 60

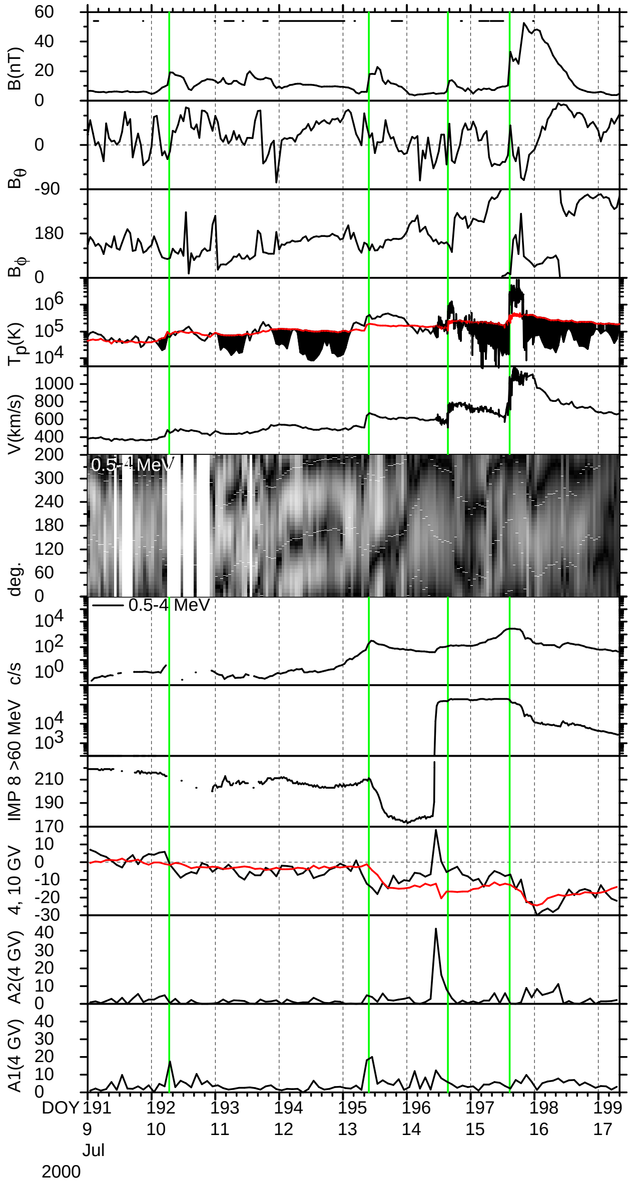

Fig. 2. Similar observations for July 9-17, 2000.

MeV particles. This shows a small enhancement following an M7/3B solar event at N18^{o}E09^o at 07 UT on September 23 (the source of the shock/ICME on September 24-26) as well as the Forbush decrease associated with passage of the shock and ICME. In summary, this is another example where bidirectional cosmic ray flows occur inside an ICME and are accompanied by bidirectional $\sim$ 1 MeV ions. Note that these flows occur in quite different particle populations – galactic cosmic rays and particles accelerated by a shock following a solar event.

Other interesting examples of bidirectional particle flows occurred in mid-July 2000, as shown in Figure 2 in a similar format to Figure 1. Again, the solar wind data are from ACE except for an interval of WIND plasma data on July 14-15 when ACE data are not available. Four interplanetary shocks followed by regions of low T_p plasma suggestive of the associated ICMEs passed the Earth during this interval (the temperature depression on July 14 is rather modest however). Horizontal bars (top panel) indicate intervals of bidirectional $\sim$ 1 MeV ions at IMP 8, which was in the solar wind during most of the interval in Figure 2. These correspond closely with the low T_p /ICME regions, though they are notably absent on July 16. The IMP 8 anti-coincidence guard rate here is spread over two panels. The most prominent feature in the upper panel (logarithmic scale) is the intense, so-called "Bastille Day", particle event on July 14, associated with an X5.7/3B flare at N22^{o}W07^o commencing at 1003 UT which is clearly linked via the particle intensity-time profile with the shock on July 15 and subsequent ICME (note the typical particle depression inside the ICME). The lower panel (linear scale) shows modulations in the counting rate associated with galactic cosmic rays, in particular depressions associated with passage of the shocks and ICMEs, similar to those inferred from the NM data at 4 and 10 GV shown in the panel below. The Bastille Day event was sufficiently energetic that it was detected as a "ground-level event" by the NM network (see the brief enhancement at 4 GV). The biggest cosmic ray depression during this period occurred during the ICME associated with the Bastille Day event. We identify two intervals of bidirectional flows in the NM data. The first (July 14, 11-17 UT) occurred during the onset phase of the Bastille Day event. The Earth was apparently in the ICME following the July 13 shock at this time, so a reasonable explanation is that highly-energetic particles from the Bastille Day event were trapped and mirrored on looped magnetic field lines inside this ICME, as has been frequently observed at lower energies (e.g., Richardson and Cane, 1996). Similar flows for another GLE, on May 2, 1998, which was also injected into an ICME (also evident from our analysis of this event) were reported by Danilova et al. (1999). The second period of CR bidirectional flows (July 15, 21 UT - July 16, 10 UT) occurred during the deepest part of the Forbush decrease within the ICME associated with the Bastille Day event. Thus again, the observations in Figure 2 illustrate the close association of bidirectional flows at $\sim$ 1 MeV and at cosmic ray energies with ICMEs.

Summarizing the relationship between bidirectional particle flows and ICMEs, between January 1996 and March 2001, we find 43 intervals of clear bidirectional $\sim$ 1 MeV ion flows (as defined by Richardson et al. (1999), i.e. durations > 1.25 hours with bidirectional flows observed for at least 25% of the total interval). Sixty percent (23) of these events were associated with ejecta we have identified independently in WIND or ACE solar wind plasma and magnetic field data. Seven other events (16%) occurred in slow solar wind with no other evidence of ICME signatures, 4 events (9%) within corotating interaction regions, 4 (9%) within high-speed streams, one (2%) between a shock and the related ICME, and one (2%) closely followed an ICME. Thus, as was found previously (e.g., Richardson, 1994), bidirectional MeV ion flows are predominantly, though not exclusively, associated with ejecta/ICMEs. Ten (67%) of the 15

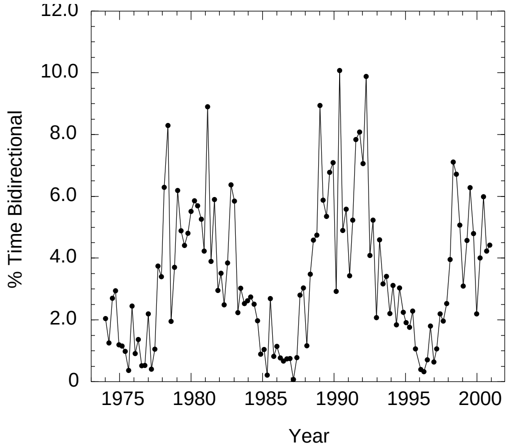

Fig. 3. Percentage of the time when bidirectional 0.5-4 MeV ion flows were detected by IMP 8 in the solar wind.

clear bidirectional MeV ion events in October 1997 - October 1998 were concurrent with previously-reported bidirectional solar wind electron events observed by the ACE spacecraft. In Figure 1, BDEs were observed from Sep. 25, 01 UT to September 26, 1930 UT. Although this is reasonably consistent with the ICME interval, the BDE onset time appears to be more closely related to shock passage than with the leading edge of the ICME.

As noted above, we identified 7 intervals of bidirectional CR flows at ~ 4 GV with durations > 2 hours in January 1997 - November 1998. Of these, six were clearly associated with ICMEs we have identified in the solar wind data. All events (5) during the period when ACE BDEs have been reported occurred during BDEs. Of the 5 events for which simultaneous IMP 8 ~ 1 MeV ion anisotropy data are available (i.e., when IMP 8 was in the solar wind), four were accompanied by bidirectional ~ 1 MeV ion flows. Hence, again we note a close association between bidirectional cosmic ray flows and those at lower energies, and with ICMEs. Note however, that only a small fraction ($\sim 10\%$) of the 62 ICMEs we identified in the solar wind data in January 1997 - November 1998 were associated with bidirectional CR flows.

Finally, Figure 3 shows that fraction of the time when 0.5-4 MeV ion bidirectional flows are present in the solar wind during the IMP 8 mission has followed solar activity levels. This variation arises (Richardson et al., 1999) because there are more ICMEs in the solar wind as activity increases, and interplanetary particle intensities are generally higher. In the current cycle, the rate of bidirectional flows is slightly lower than in the previous two solar maxima, consistent with the lower level of activity during this cycle.

4 Conclusions

Consistent with Richardson et al. (2000), we find that bidirectional galactic cosmic ray flows observed by the NM network tend to be associated with ICMEs and with bidirectional flows of lower energy particles. However, they are only present in a small fraction (∼10%) of the ICMEs which pass the earth. The fraction of the time bidirectional ~ 1 MeV ion flows have been observed in the solar wind by IMP 8 since the beginning of the spacecraft mission shows a clear correlation with solar activity levels.

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